Food Production and Preparation
The state of the art

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MELiSSA WORKSHOP
Science and Technologies on Regenerative Life-Support
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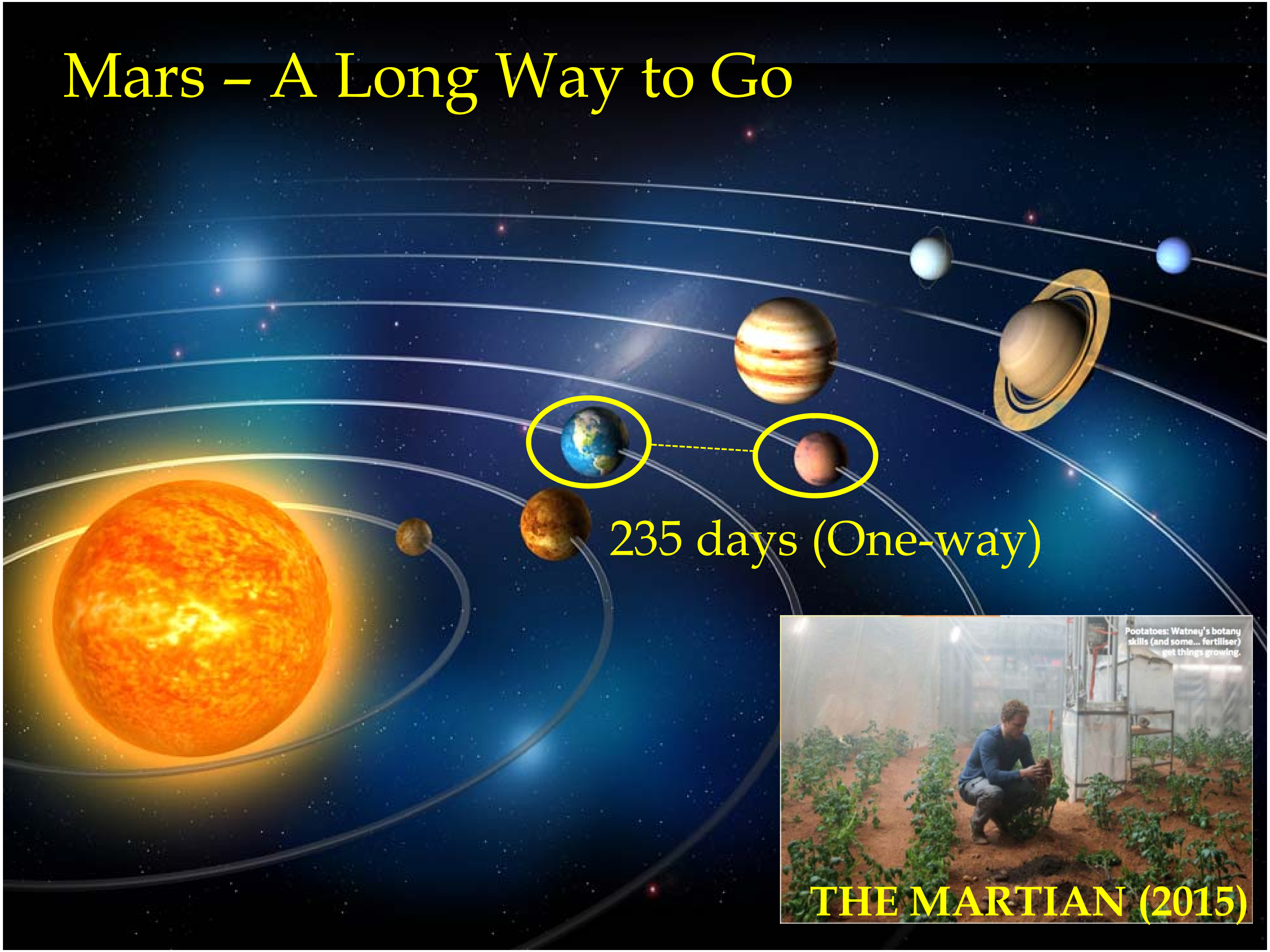

Mars – A Long Way to Go
235 days (One-way)
Pootatoes: Watney's botany skills (and some... fertiliser) get things growing.
THE MARTIAN (2015)

DAILY INPUTS - NOMINAL	kg
Oxygen	0.84
Food Solids	0.62
Water in Food	1.15
Food Prep Water	0.79
Drink	1.62
Hand/Face Wash Water	1.82
Shower Water	2.45
Clothes Wash Water	2.50
Dish Wash Water	2.45
Flush Water	0.50
TOTAL	14.74

Courtesy of NASA – M. Kliss

~ 5.0 - 15.0 kg per person-day

Up to 5.5 metric tons per person-year

DAILY OUTPUTS - NOMINAL	kg
Carbon Dioxide	1.00
Respiration and Perspiration Water	2.28
Urine	1.50
Feces Water	0.09
Sweat Solids	0.02
Urine Solids	0.06
Feces Solids	0.03
Hygiene Water	3.68
Clothes Wash Water	1.90
Clothes Wash Latent Water	0.60
Other Latent Water	0.65
Dish Wash Water	2.43
Flush Water	0.50
TOTAL	14.74

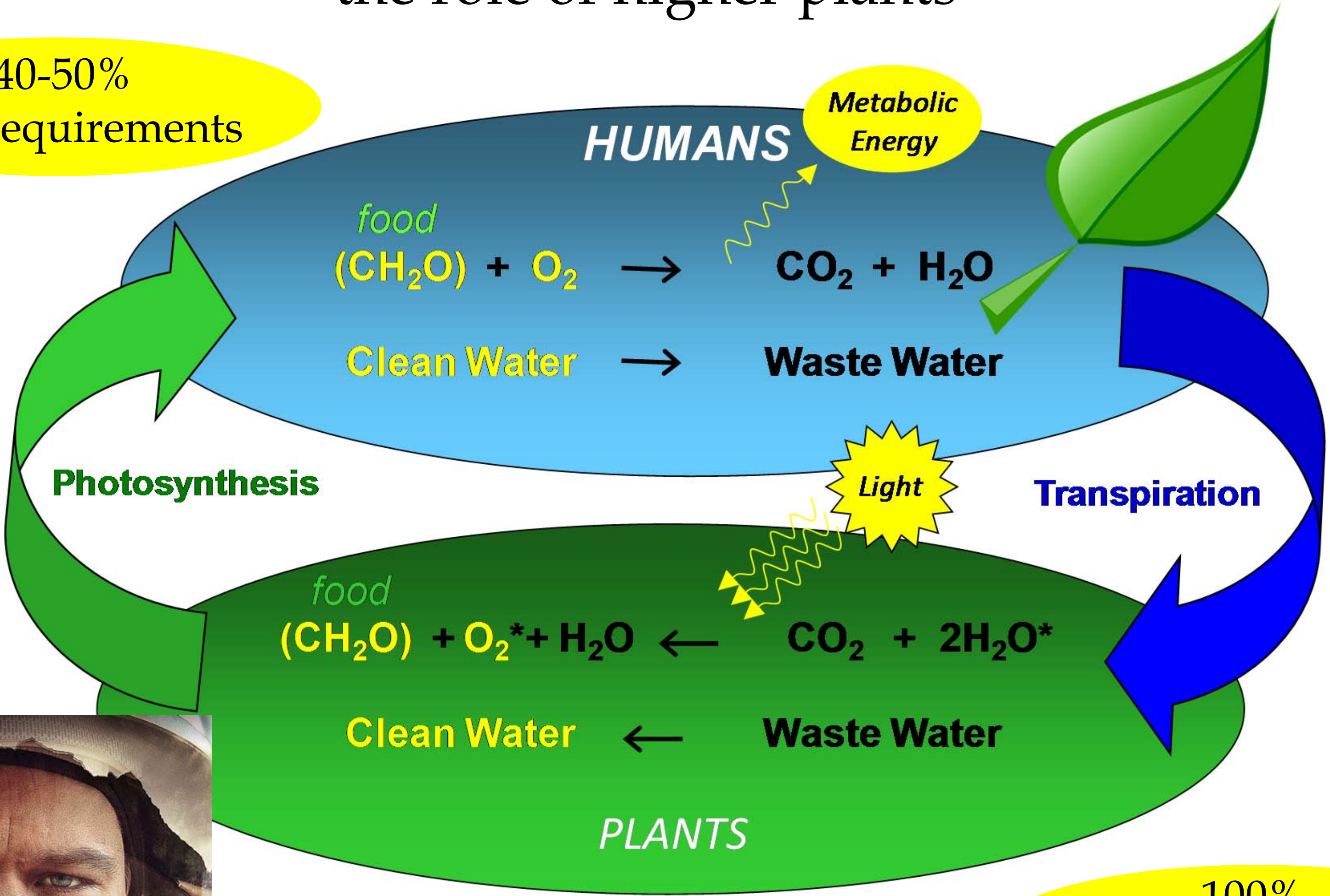
Astronaut Scott Kelly drunk around 730 litres of his own sweat and urine during 1 year mission on ISS

Human beings and Higher plants: a complementary relationship

Why higher plants should be less important in any environment other than Earth?

Closed regenerative Life-Support Systems: the role of higher plants

40-50%
food requirements

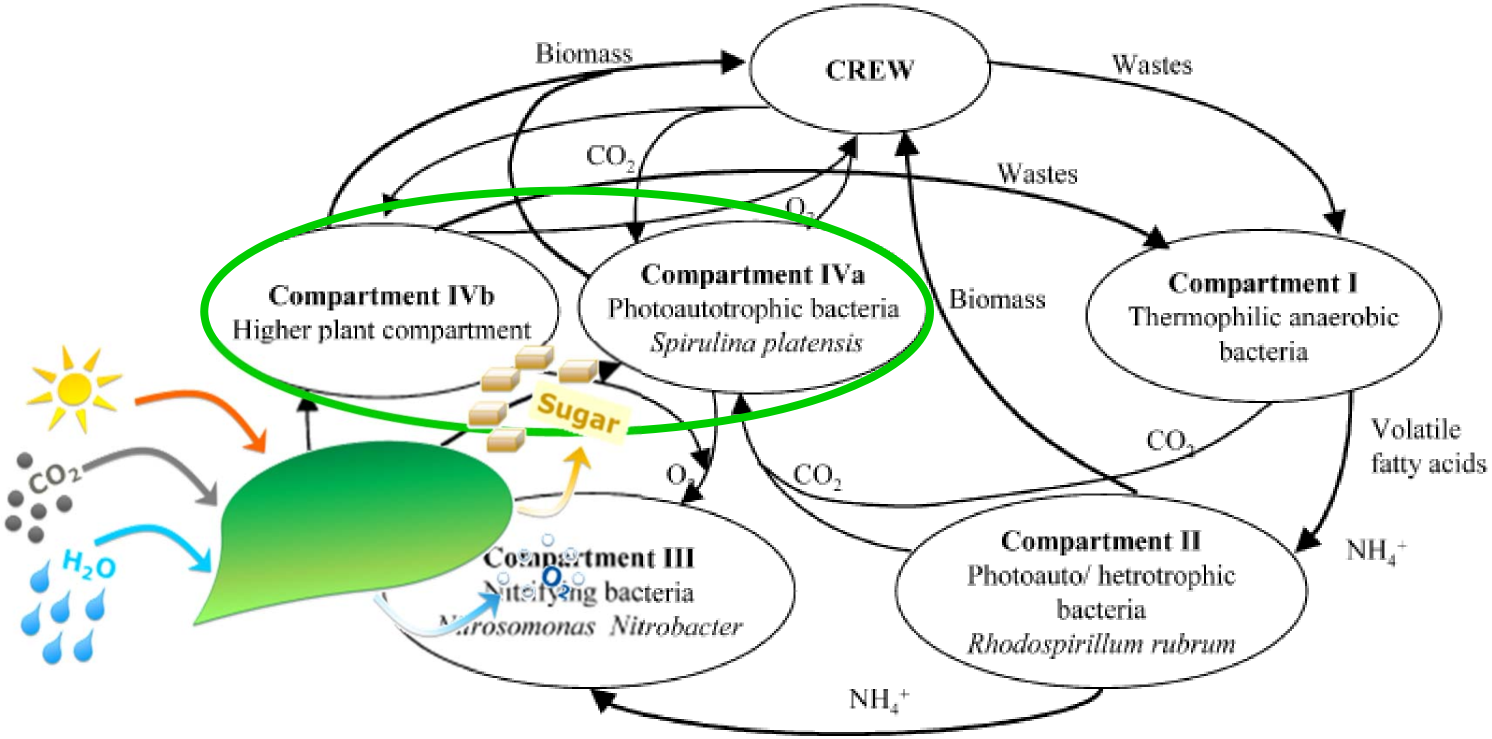


100%
air and water recycling

Plus:
- crew recreation
- mitigation of psychological stress

Courtesy of NASA – R. Wheeler

MELISSA - Micro-Ecological Life Support System Alternative



Gòdia et al., 2002
Journal of Biotechnology, 99:319-330

The roadmap (C-IVb)

PHASE 1 BASIC RESEARCH & DEVELOPMENT

- Menu Preliminary definition
- Food processing and characterization
- Crop selection and characterization
- Crop Wastes management
- Crop nutrition management
- Modelling plants growth
- Design of plant metabolic chamber

PHASE 2 PRELIMINARY FLIGHT EXPERIMENT

- Definition of requirements for future scientific activities
- Definition of standard experimental design
- Preparation of scientific flight experiment

PHASE 3 GROUND DEMONSTRATION

- Operation of HPC prototype in MELiSSA Pilot Plant
- Design of a Moon greenhouse
- Design of precursor Food Production Unit

PHASE 4 TERRESTRIAL TRANSFER

- Commercial application of HPC

PHASE 5 EDUCATION AND COMMUNICATION

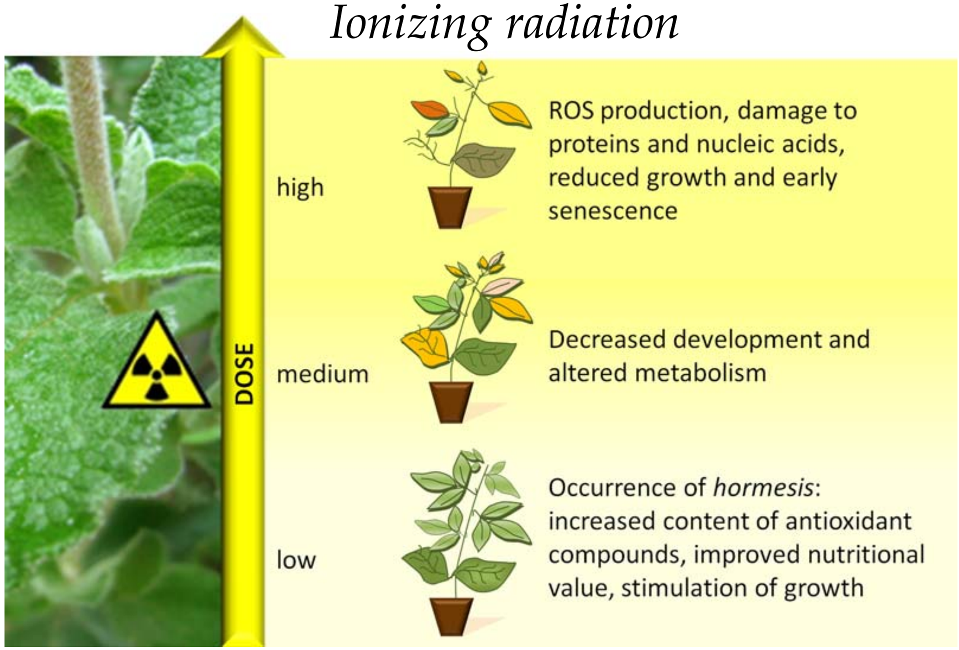
- National challenge
- Pool of PhDs

Higher plants in Space: constraints

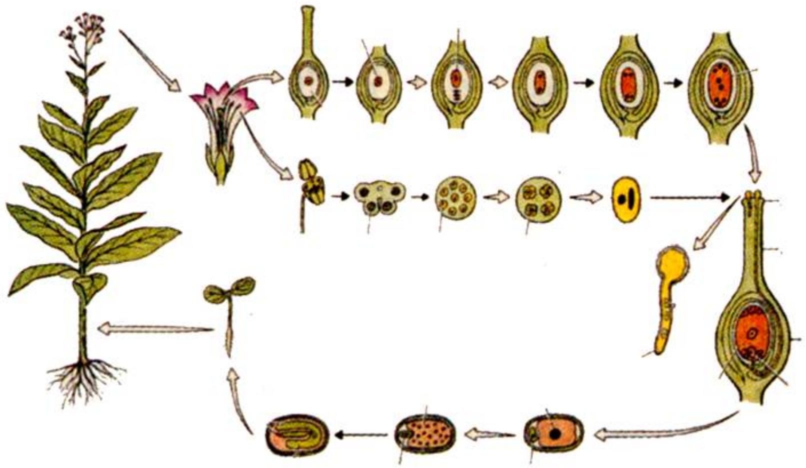
General
- Complexity
- Reliability
- System integration
- Waste management
- Growth and development under:
    - Microgravity
    - Ionizing radiation
    - ....

Agronomical
- Crop/cultivar selection
- Suitable cultivation system
- Staple /salad crops
    - Food processing / shelf-life
- Pathogens
- Food quality
- Food safety
- …

Ionizing radiation



Seed-to-seed cycle



Mission constraints

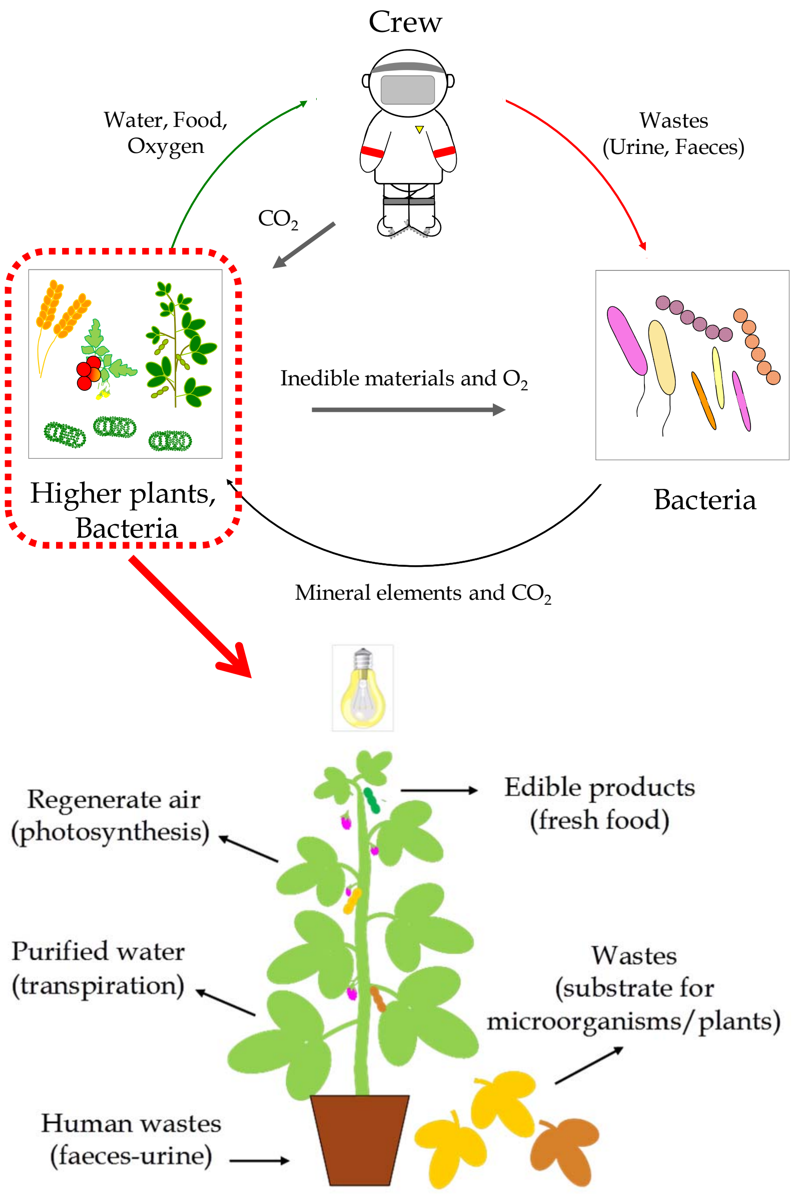
Space mission

- Mass, energy, safety, reliability
- Interface from/to other compartments
  - timing/quality and quantity of fluxes

- Interaction with the loop:
  - characterization of food chain
  - air regeneration and waste recycling
  - overall modelling

Human nutrition

- Nutritional requirements
- Physiology alterations
- Food acceptance

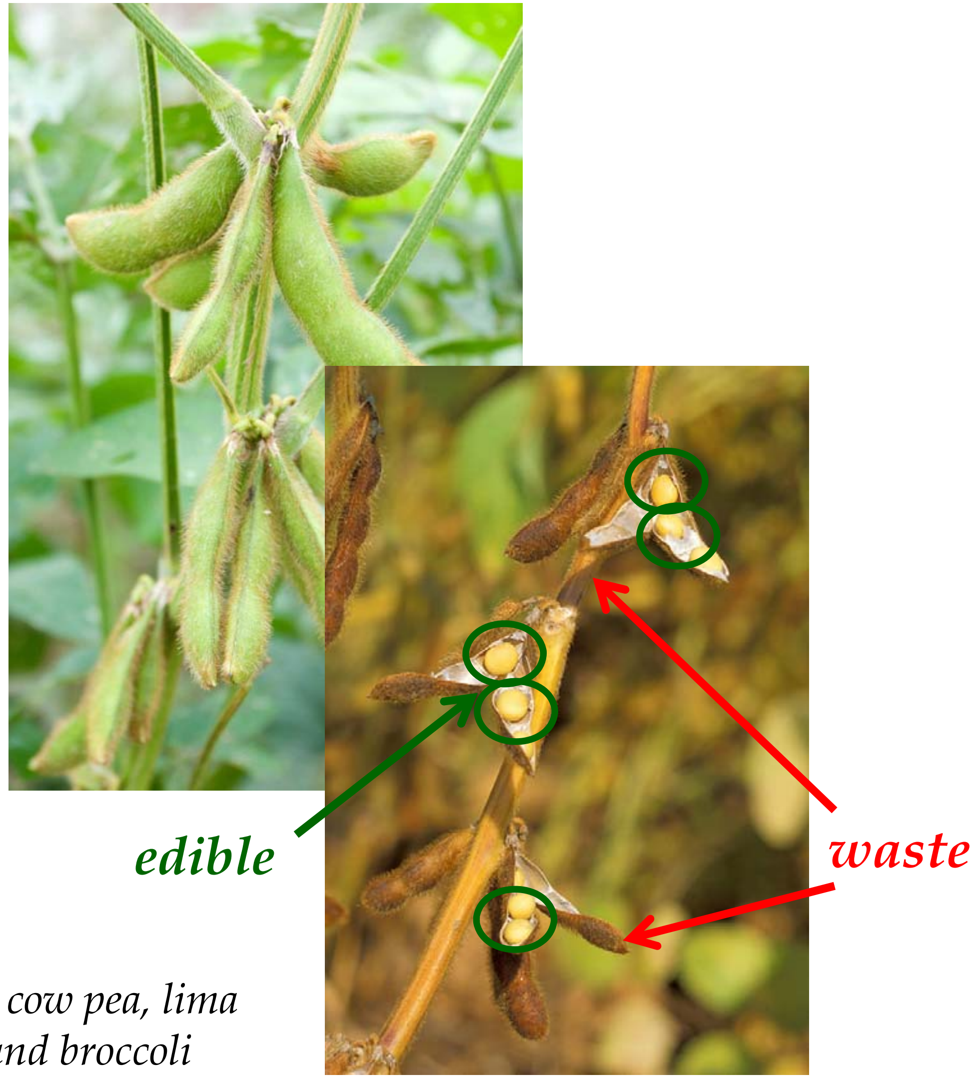


Food Production: crop selection

PHASE 1
R&D

Main selection criteria:

- Short cultivation cycle, reduced plant size
- High productivity and Harvest Index (ratio of edible and waste biomass)
- Nutritional quality
- Adaptability to closed environment
- Resistance to diseases
- Processing and storage requirements
- Human factors - appeal, taste, smell



Plus: *kale, carrot, peanut, sweet potato, chick pea, cow pea, lima bean, snap bean/dry bean, garden pea, lentil and broccoli*

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PHASE 1
R&D

Food Production: candidate crops

Staple crops

Potato
Carbohydrates

Bread wheat
Carbohydrates

Durum wheat
Carbohydrates

Soybean
Proteins

Field crops

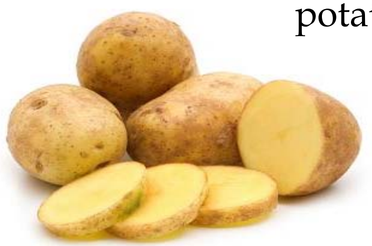
Food products

SEEDS
- Washing → Soaking → Milling → Paste boiling → Filtration (0.2 mm)
  - Soymilk → Sanitization (15 min boiling) → SANITIZED SOYMILK
  - OKARA
- Germination → SPROUTS

PHASE 1
R&D

Candidate crops: main research objectives

1. Cultivar selection
2. Environmental conditions set-up
3. Protocol for hydroponic cultivation
4. Evaluation of plant behaviour in hydroponics in controlled environment
5. Design and integration of a higher plant compartment
6. Modelling
7. Response to *Space* factors
8. Food quality assessment
9. Food processing


potato

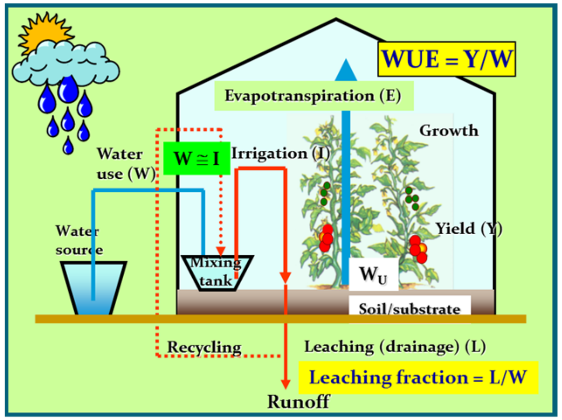

bread wheat


durum wheat

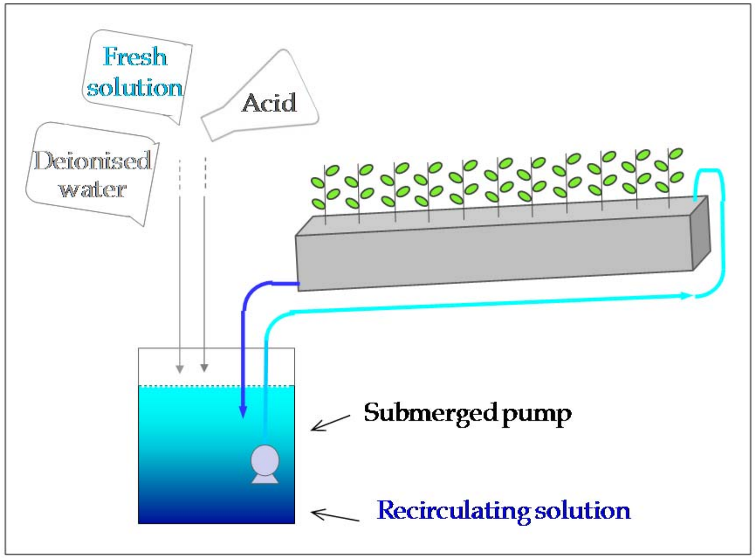

soybean

PHASE 1
R&D

Growing system: closed hydroponic



Closed-loop nutrient film technique (NFT)



Modified Hoagland & Arnon ½ strength

	mM
N	7.5
K	3.0
P	0.5
Ca	2.5
Mg	1.0
S	1.0
	µM
Fe	60.00
Mn	7.40
Zn	0.96
Cu	1.04
B	7.13
Mo	0.01

Advantages:

- Clean and sterile environment
- Faster plant growth rate
- Higher yield and quality
- Higher water and nutrient use efficiency
- Automation

Drawbacks:

- Suitable cultivars (field crops)
- Salinity build up
- Phyto-toxicity
- Contamination and spread of pathogens

Theoretical selection of cultivars: example for soybean

PHASE 1
R&D

Procedure:

- collection of data on available cultivars
- selection of the main criteria for the choice
- application of the algorithm for the ranking

Number of soybean cultivars (*N*) for which information was available per each factor, and assigned priority factors (*P*).

Criteria	*N*	*P*
Period of cultivation	29	3
Maturity group (earliness)	93	3
Level of antinutritional factors	6	3
Protein content	56	3
Sensitivity to *Sclerotinia*	40	3
Size	77	3
Suitability to industrial uses	6	3
Tolerance to *Diaporthe*	19	3
Tolerance to *Phytophthora*	33	3
Tolerance to *Rhizoctonia*	7	3
Tolerance to stresses	12	3
Yield	69	3
1000 seeds weight	72	3
Branching	11	2
Colour of *Hilum*	29	2
Sensitivity to lodging	83	2
Stalk rating	2	2
Defoliation	19	1
Dehiscence	16	1
Insertion 1st pods	40	1

$$S = \sum (Pi^{*} Xi)$$

S = final score for each cultivar

P = priority factor of the criteria

X = subclass percentage factor

De Micco et al. 2012. Adv Sp Res 49: 1415–1421

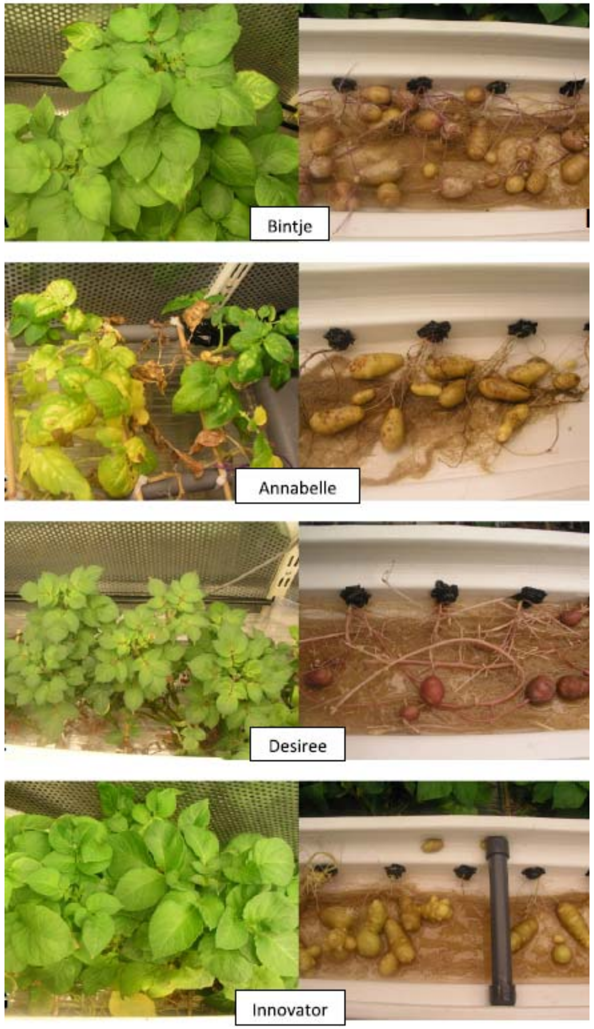
PHASE 1
R&D

Hydroponic cultivation of candidate crops: Cultivar characterization

Bread wheat

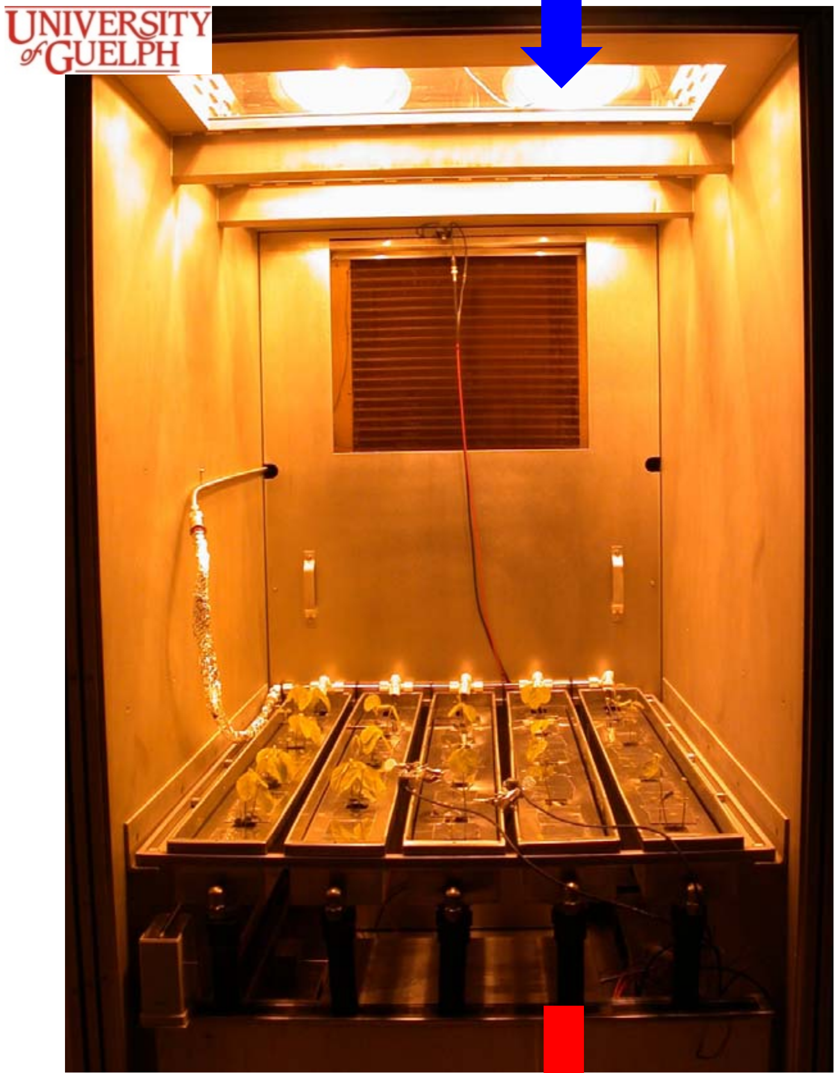
Soybean

Potato



Durum wheat

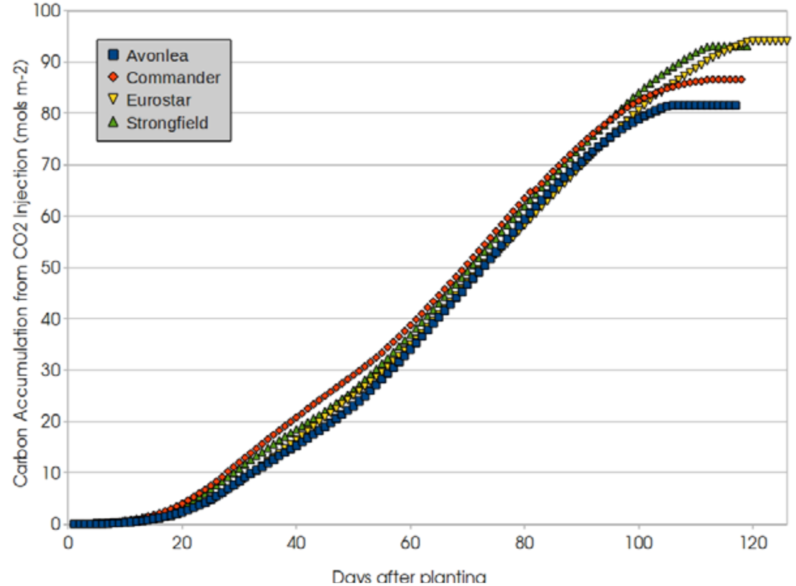
Inputs
energy, water, nutrients, O_2, CO_2



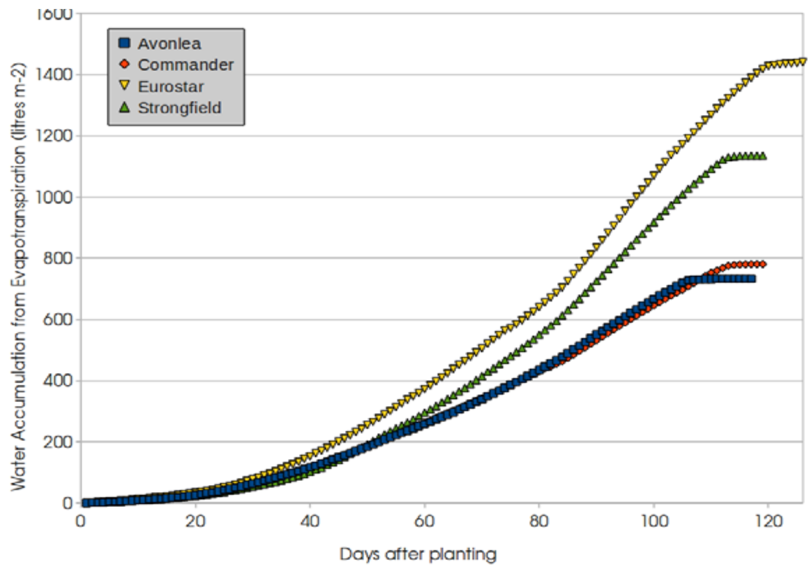
Outputs
water, O_2, CO_2, waste

Durum wheat

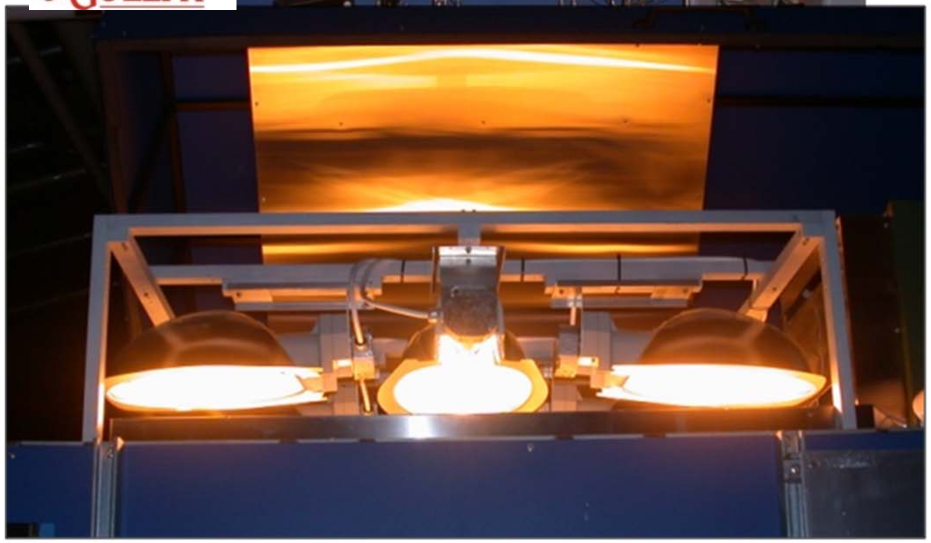
Carbon accumulation

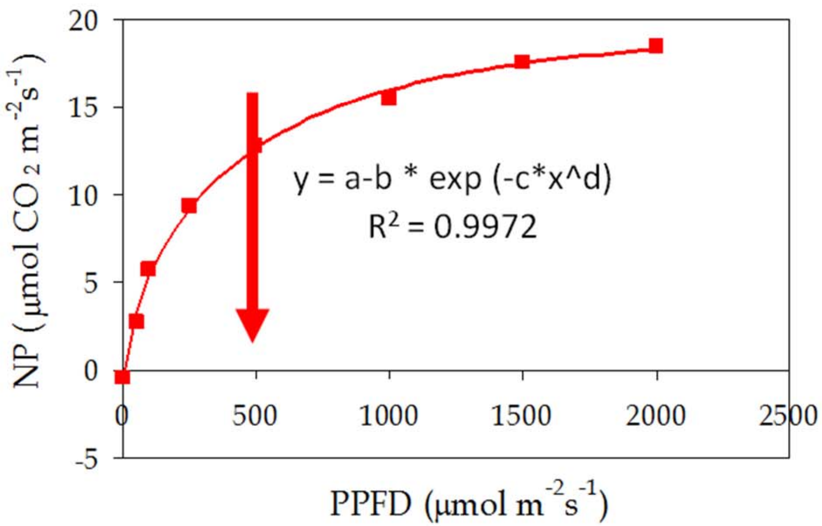


Water recovery



Crop physiology





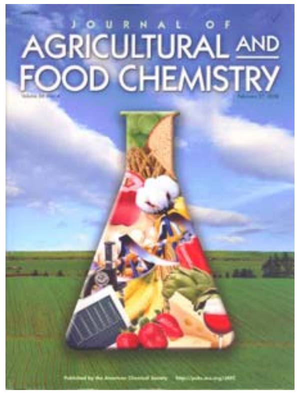
PHASE 1
R&D

Crop yield:
Hydroponics (controlled environment) *vs* Soil (open field)

	Yield – Field (t/ha)	Yield – Hydroponics (g/m^2)	Duration of growing cycle (days)
Potato	35.0	1450 [1]	127
Durum wheat	6.0	668 [2]	120
Bread wheat	5.5	1573 [3]	136
Soybean	4.0	546 [4]	133

[1] Molders *et al.*, 2012. Adv. Space Res., 50(1): 156-165
[2] Stasiak *et al.*, 2012. Adv. Space Res., 49 (12): 1684-1690
[3] Page & Feller, 2013. Adv. Space Res., 52(3): 536-546
[4] Paradiso *et al.*, 2012. Adv. Space Res., 50: 1501-1511

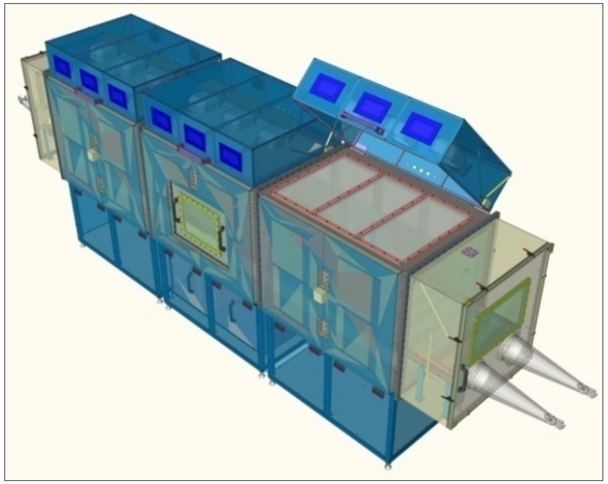
[4] Palermo et al., 2012. J. Agric. Food Chem., 60:250-255



The design of the Higher Plant Chamber (HPC)

PHASE 1
R&D

CAD drawing of the HPC Prototype by University of Guelph

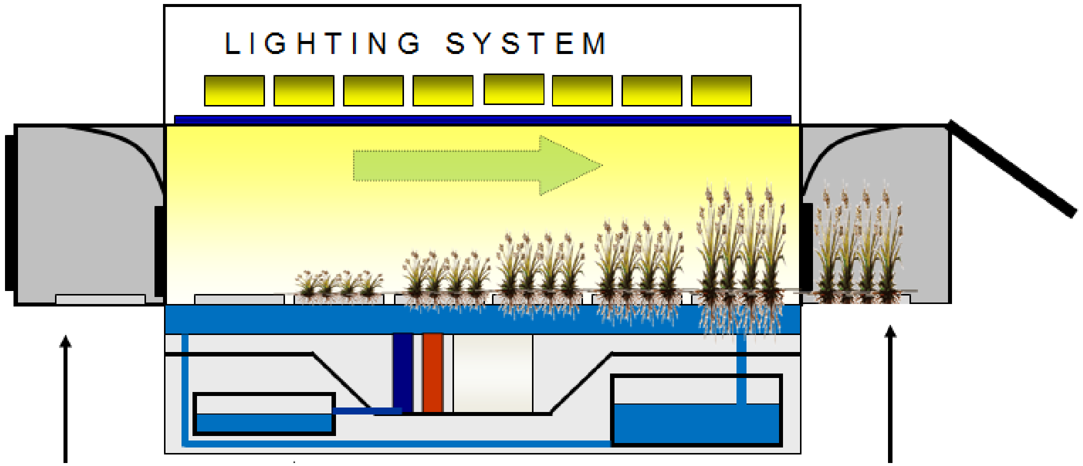


System sizing & Integration Requirements

- Sealed chamber with gas/liquid/solid connections with the loop
- Staggered plantation system
- 3 crops selected for initial integration tests (wheat, beet, lettuce)
- Biomass production: 20% of diet targeted for MPP

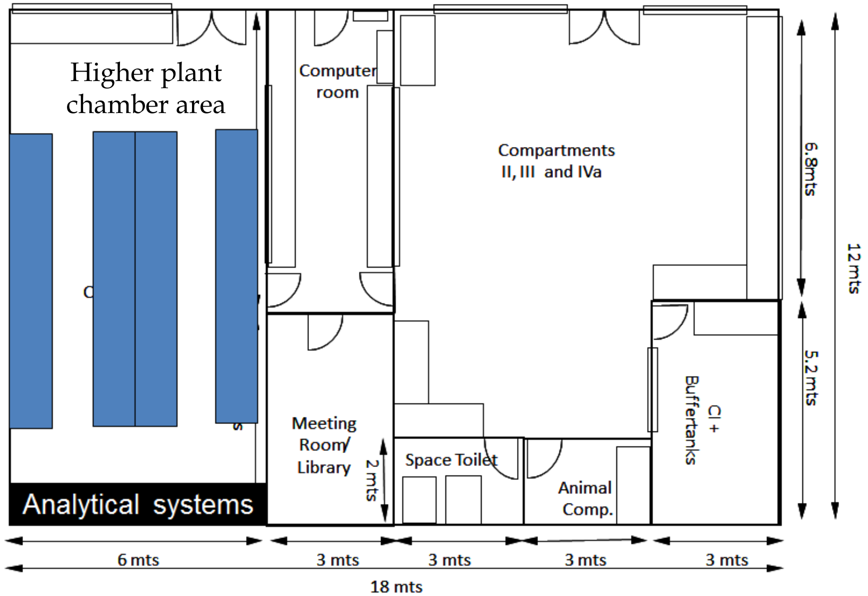
Technical Specifications

- Lighting
  - Spectrum (PAR:400-700nm)
  - Intensity (PPFD)
  - Photoperiod
- Nutrients
  - Macro: C, H, O, N, P, K, Ca, Mg, S
  - Micro: Fe, Zn, B, Cu, Cl, Mn Mo
- Atmospheric Conditions
  - Temperature (15-28 ºC)
  - Humidity (60-80%)
  - Ventilation
  - CO_2 / VOCs

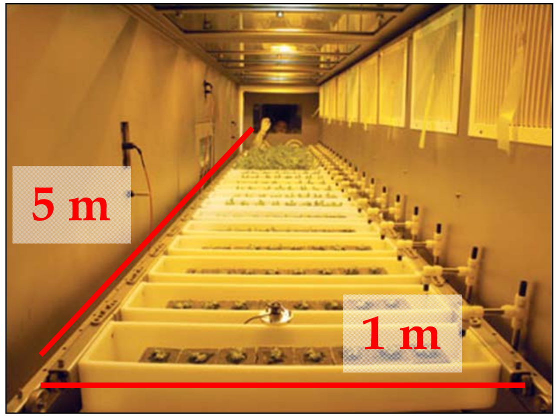


MELiSSA
PHASE 3
GD

The HPC at the MELiSSA Pilot Plant (MPP)



- Volume: 7.35 m^3
- Plant Growing Area: 5 m^2
- Light: 6x600 (HPS) + 3x400 (MH) Watt
- Temperature: 15 - 30C $\pm$ 0.2C
- CO_2: ambient to 6000 $\pm$ 10 ppm
- O_2: ambient
- RH: 50 to 95% $\pm$ 5%



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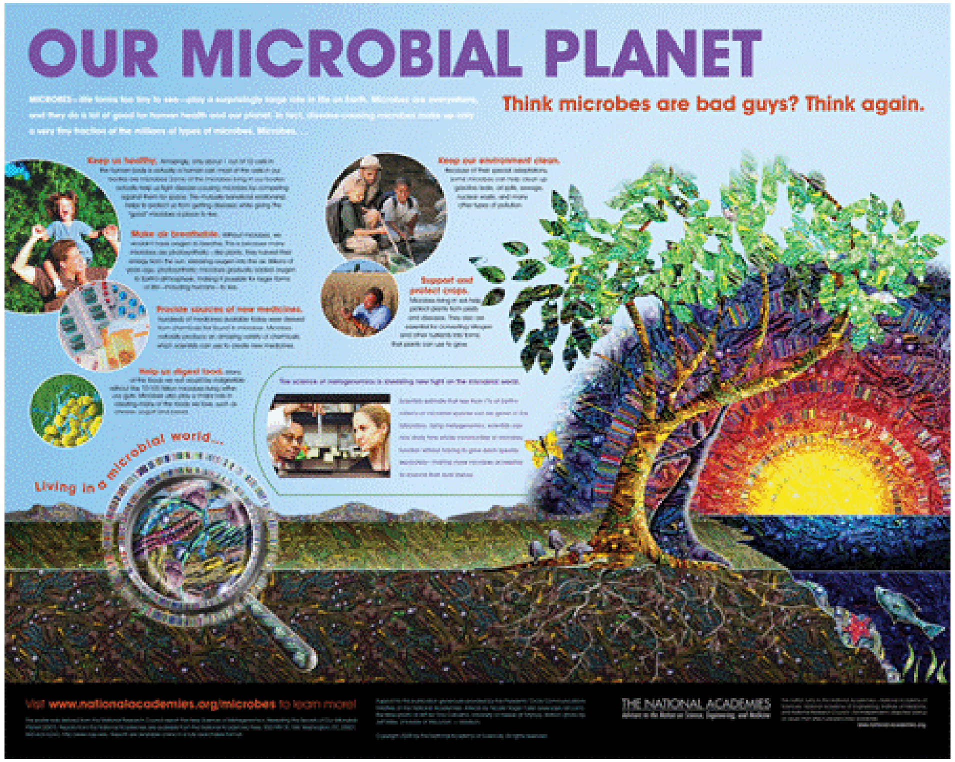
PHASE 1
R&D

Improving cultivar selection and hydroponic production: effects of beneficial microorganisms on crop production in hydroponic

WHY?

- Soil microorganisms are responsible for driving nutrient and organic matter cycling, soil fertility, soil restoration, plant health and ecosystem primary production.
- Beneficial microorganisms promote nutrient mineralization and availability, produce plant growth hormones, are antagonists of plant pests, parasites or diseases enhance plant growth.



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PHASE 1
R&D

Root nodulation and seeds yield and quality of Soybean plants inoculated with *B. japonicum*

Aim

- to evaluate the effect of inoculation with *Bradyrhizobium japonicum* (soybean bacterial symbiont) in 2 hydroponic systems (NFT and cultivation on rockwool) with urea as alternative N-source to nitrate

Results

- Root inoculation did not influence plant performance
- Cultivation on rockwool positively influenced root nodulation and plant growth and yield compared to NFT
- Urea improved root symbiosis but not plant growth and yield






MELiSSA PHASE 1 R&D

Root inoculation with plant growth-promoting organisms (4 crops)

CULSEL

Myco Madness microbial mix
(Humboldt nutrients)

Bacteria
Bacillus licheniformis
Bacillus azotoformans
Bacillus megaterium
Bacillus coagulans
Bacillus pumilus
Bacillus thuringiensis
Bacillus stearothermophilus
Paenibacillus polymyxa
Paenibacillus durum
Paenibacillus florescence
Paenibacillus gordonae
Azotobacter polymyxa
Azotobacter chroococcum
Pseudomonas aureofaciens

Yeast
Saccharomyces cerevisiae

Mycorrhiza
Glomus intraradices
Glomus mosseae
Glomus aggregatum
Glomus etunicatum
Glomus clarum
Glomus deserticola
Gigaspora margarita
Gigaspora brasilianum
Gigaspora monosporum

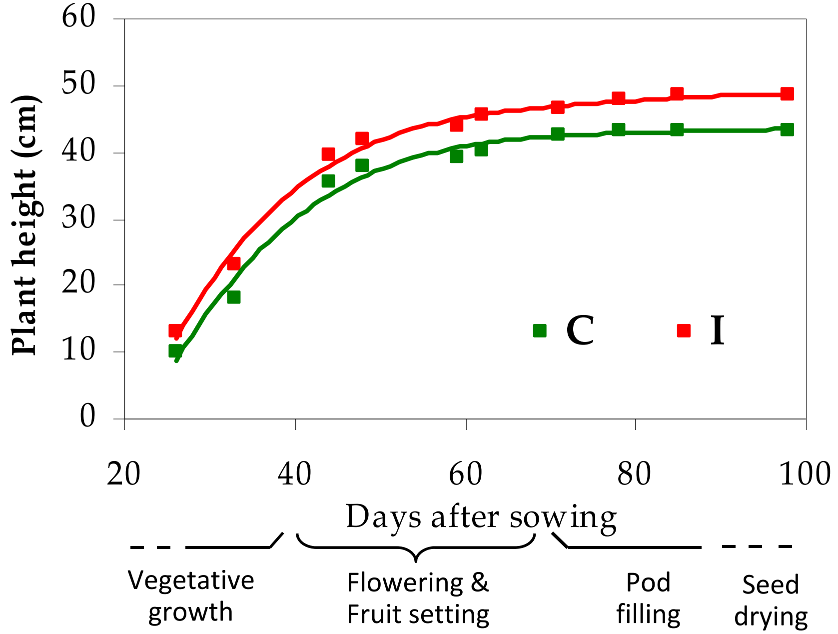
Trichoderma
Trichoderma harzianum
Trichoderma koningii

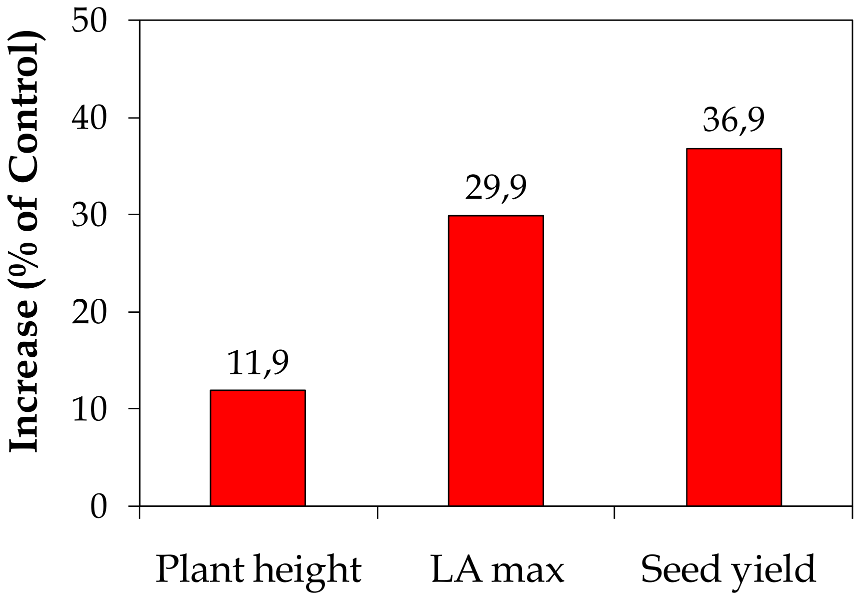
- *'**Plant biostimulants** contain substance(s) (Humic substances, Seaweed extract, Free amino acids…) and/or microorganisms (Arbuscular Mycorrhizal Fungi, Trichoderma spp., and Plant Growth Promoting Rhizobacteria) which enhance nutrient uptake, efficiency, tolerance to abiotic stress, and crop quality, with no direct action on pests'*

  [European Biostimulants Industry Council (EBIC), 2012]

Plant growth and Seed yield

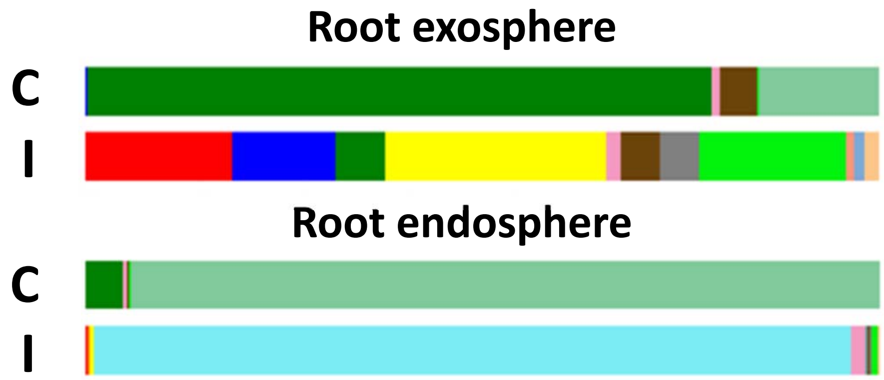
PHASE 1
R&D





Rhizosphere microbiome analysis

PHASE 1
R&D



Legend	Kingdom	Phylum	Class	Order	Family	Genus
	Bacteria	Actinobacteria	Actinobacteria	Actinomycetales	Corynebacteriaceae	Corynebacterium
	Bacteria	Actinobacteria	Actinobacteria	Bifidobacteriales	Bifidobacteriaceae	
	Bacteria	Bacteroidetes	[Saprospirae]	[Saprospirales]	Chitinophagaceae	
	Bacteria	Firmicutes	Bacilli	Bacillales	Staphylococcaceae	Staphylococcus
	Bacteria	Proteobacteria	Alphaproteobacteria	Rhizobiales	Brucellaceae	Ochrobactrum
	Bacteria	Proteobacteria	Alphaproteobacteria	Rhizobiales	Hyphomicrobiaceae	Devosia
	Bacteria	Proteobacteria	Alphaproteobacteria	Rhizobiales	Rhizobiaceae	Agrobacterium
	Bacteria	Proteobacteria	Alphaproteobacteria	Rhodospirillales	Rhodospirillaceae	
	Bacteria	Proteobacteria	Betaproteobacteria	Burkholderiales	Comamonadaceae	
	Bacteria	Proteobacteria	Betaproteobacteria	Burkholderiales	Comamonadaceae	Acidovorax
	Bacteria	Proteobacteria	Betaproteobacteria	Burkholderiales	Comamonadaceae	Curvibacter
	Bacteria	Proteobacteria	Betaproteobacteria	Burkholderiales	Oxalobacteraceae	
	Bacteria	Proteobacteria	Betaproteobacteria	Methylophilales	Methylophilaceae	
	Fungi	Ascomycota				

Sheridan et al., 2016 - Microbial Ecology, in press

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MELISSA PHASE 1 R&D

Hydroponic Subsystem Engineering

Objective

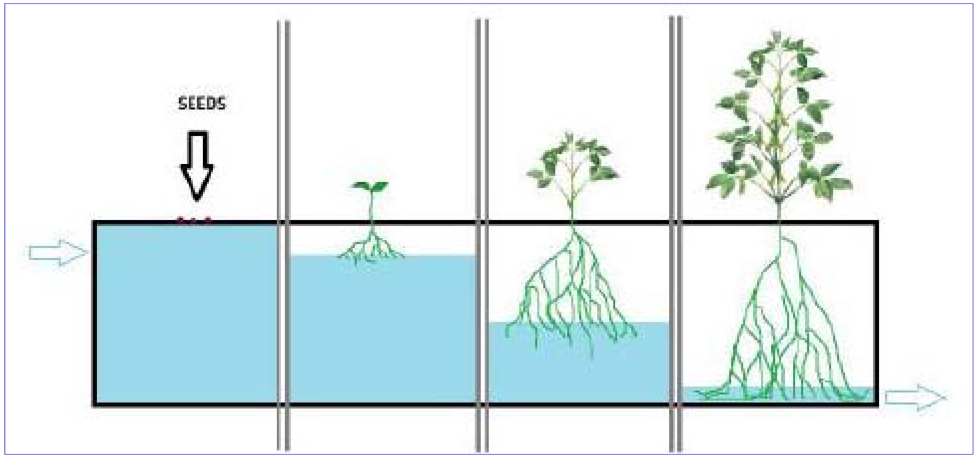
To design a modified hydroponic system to address critical modelling requirements in HPC

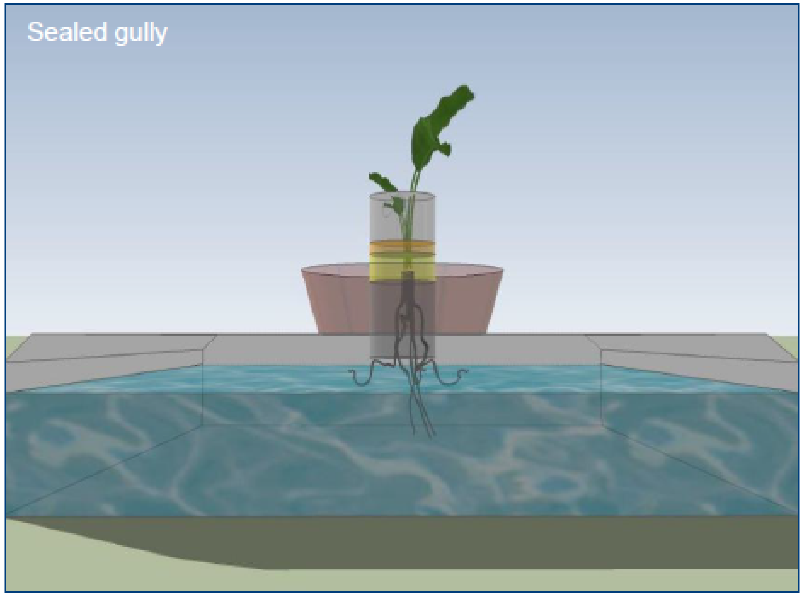
Results

Hybrid hydraulic system: deep water culture with a variable level in sealed gully

Parametric model to obtain uniform nutrition solution flow

A functional breadboard for tests on potato and durum wheat





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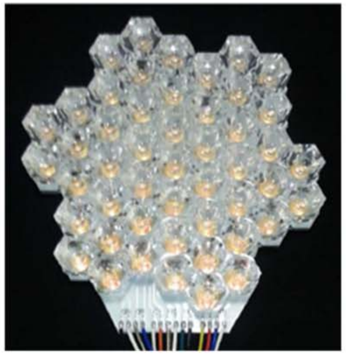
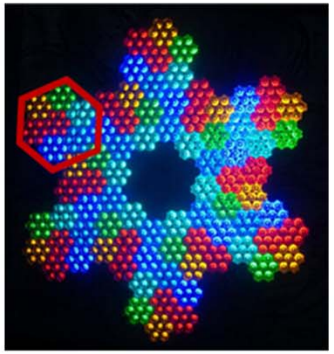
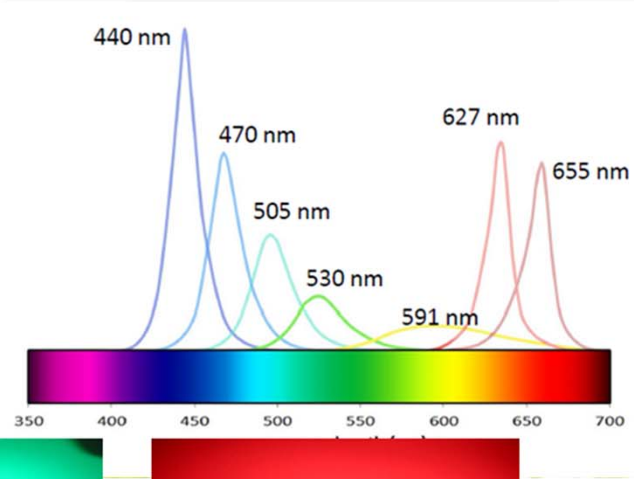
PHASE 1
R&D

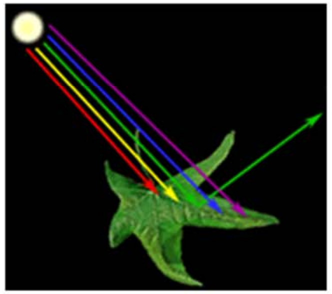
Optimizing light recipes













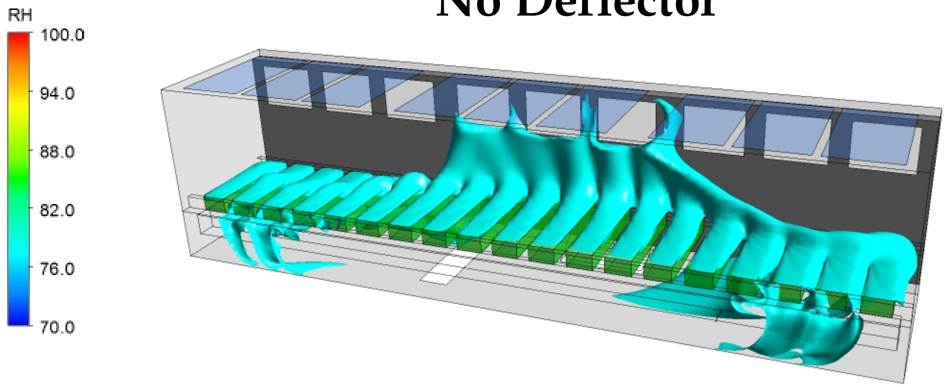
MELISSA

PHASE 3
GD

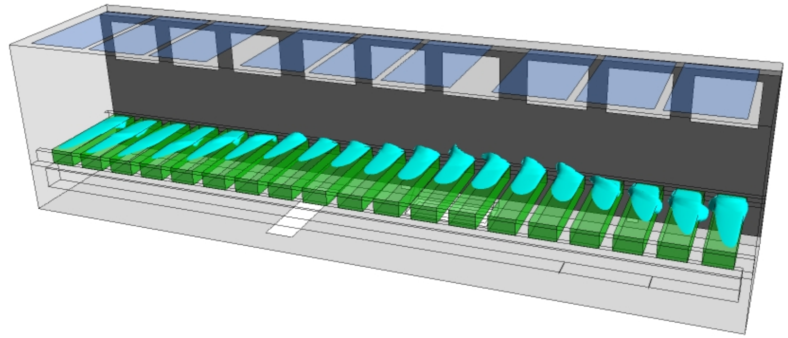
Study and mitigation of HPC:
Heating, Ventilating and Air Conditioning

Relative Humidity

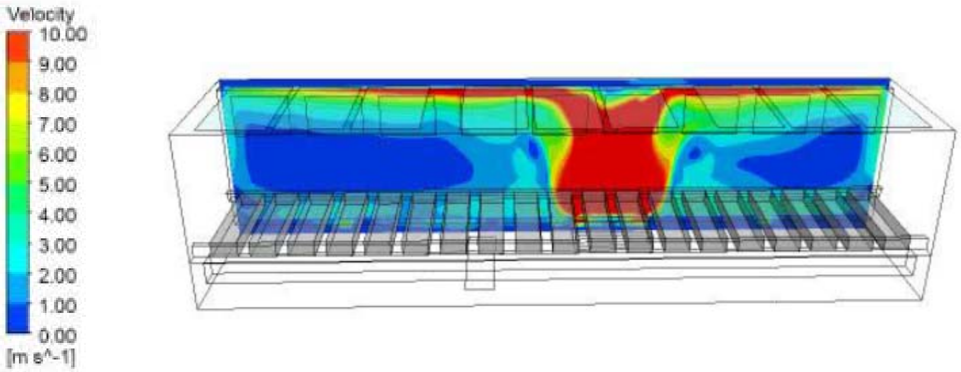
No Deflector

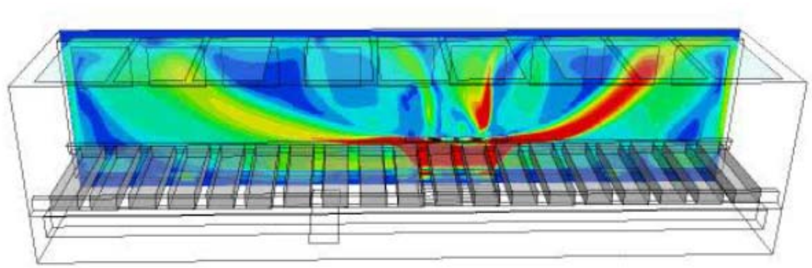


Deflector



Air velocity





Computational fluid dynamics
(CFD) applied to the HPC climate conditioning

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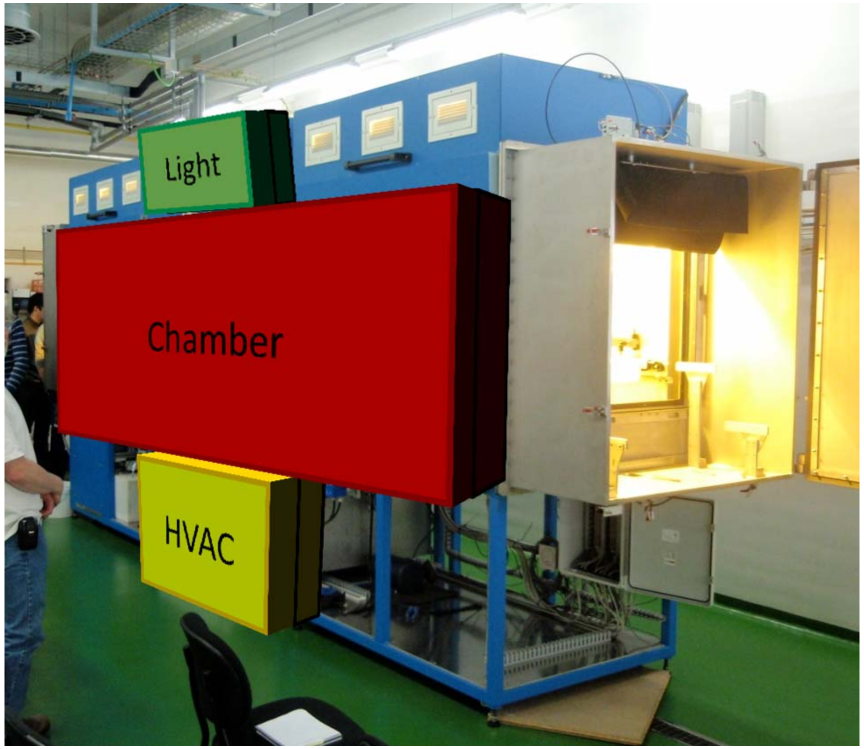
PHASE 3
GD

MELiSSA Pilot Plant
Higher Plant Compartment Integration

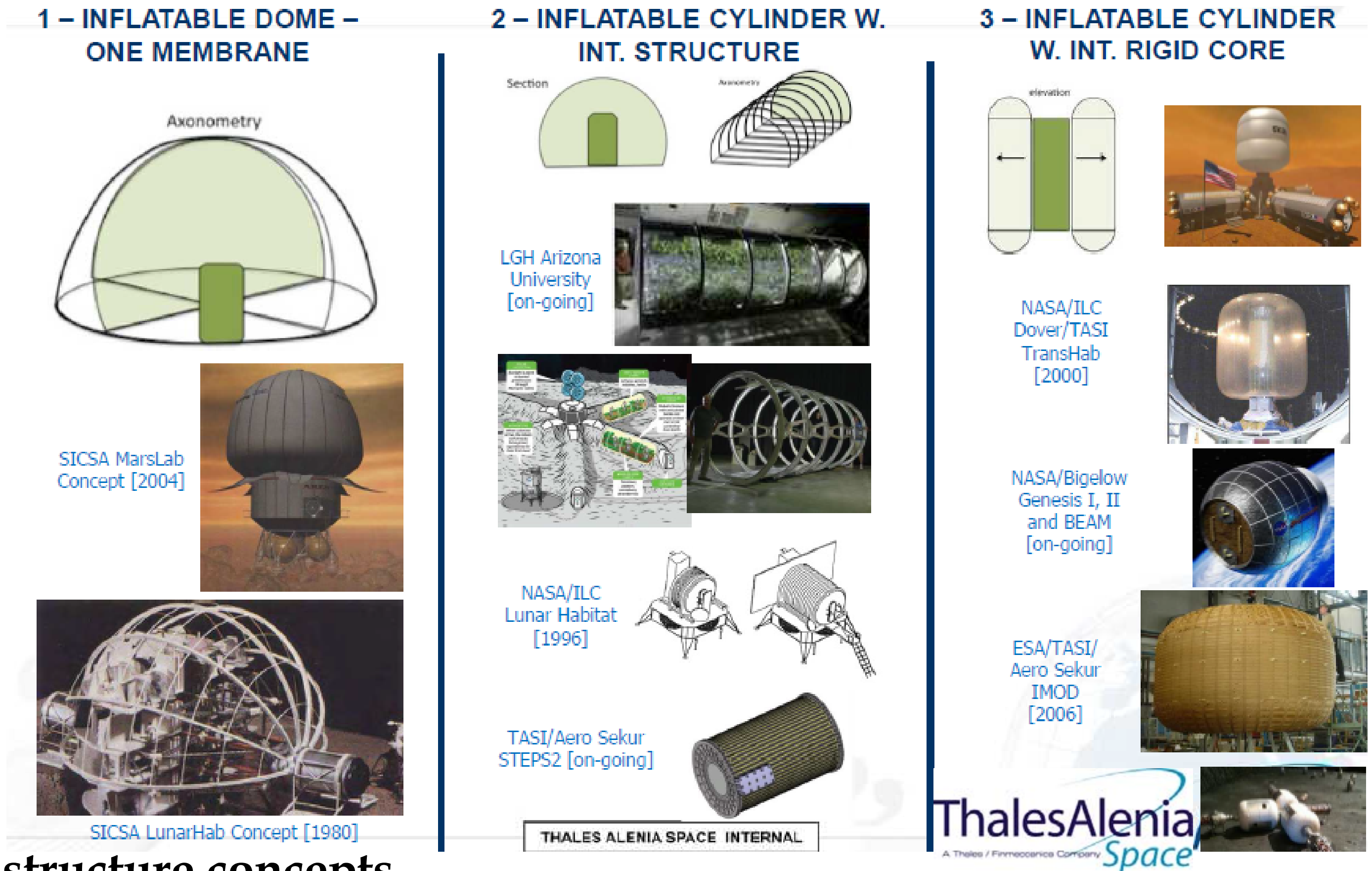
Challenges:
- Knowledge model (under development)
- Predictive control (control strategies)
- Interfaces with other compartments



MELISSA
PHASE 3
GD

Lunar Greenhouse Study

Preliminary Study of a lunar surface greenhouse in the MELiSSA framework

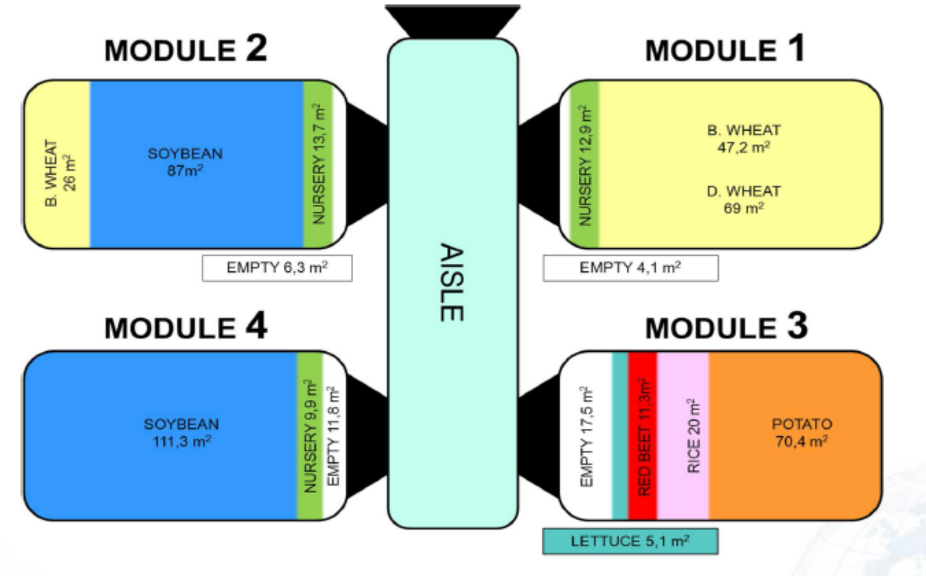


Primary structure concepts

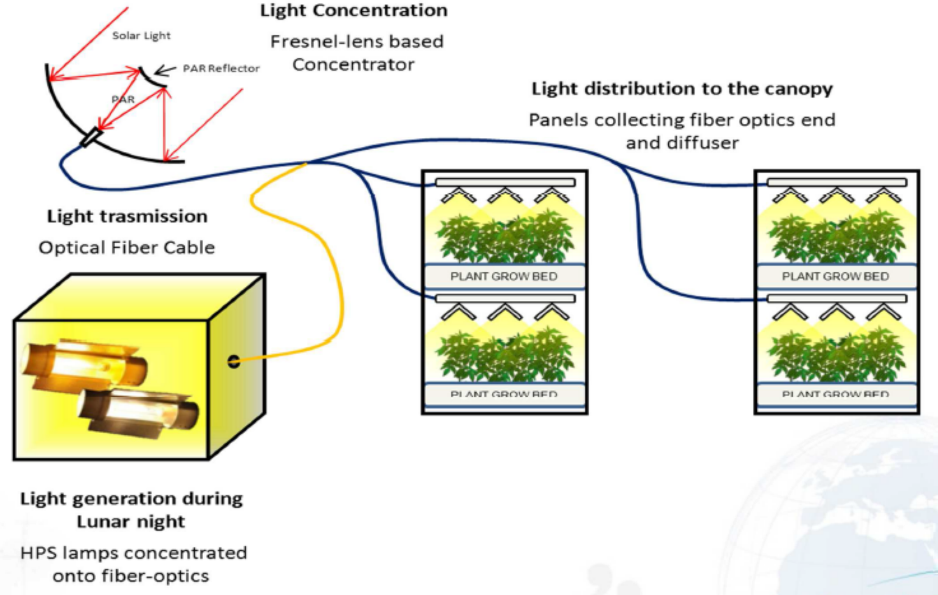
Lunar Greenhouse Study

PHASE 3 GD

- Two major trade-offs:
  - Artificial *vs.* natural illumination
  - Mono *vs.* Multicrop



Baseline monocrop solution modules composition



Hybrid illumination solution description

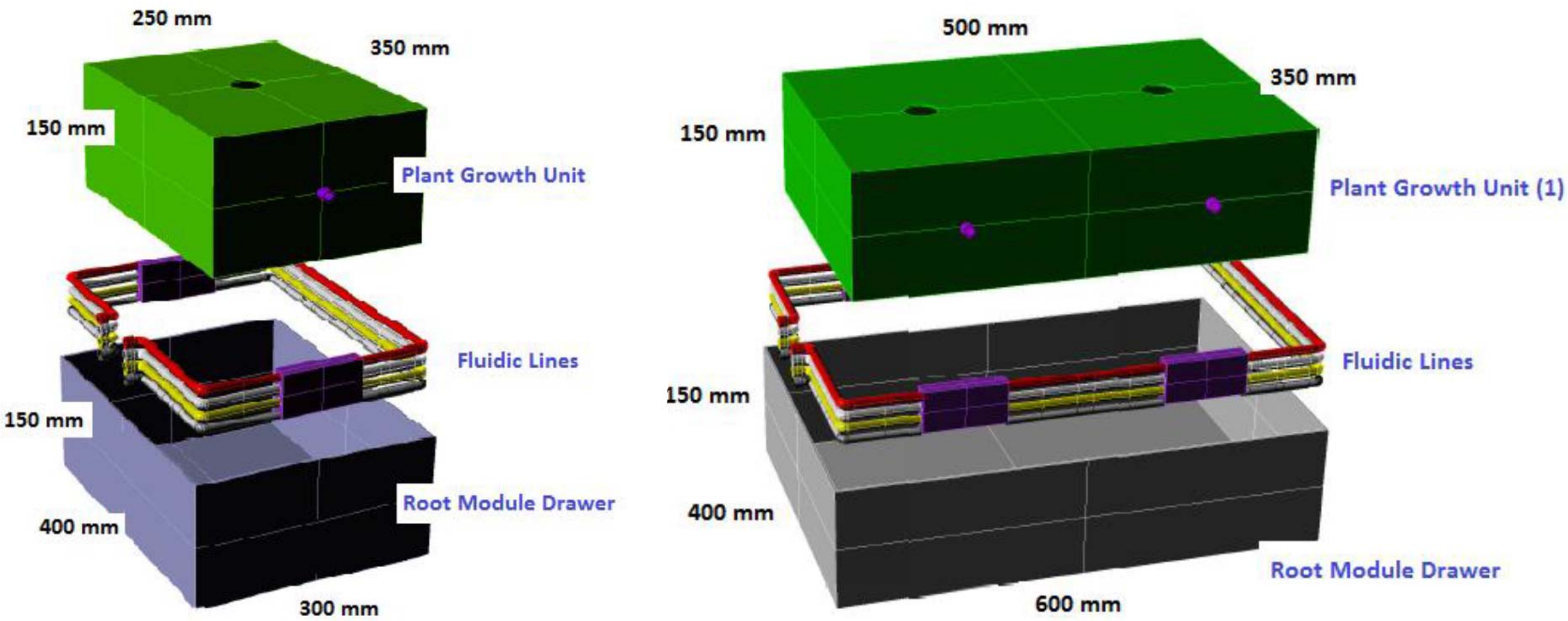
ThalesAlenia Space

PHASE 3
GD

Flight experiment preparation: Precursor Food Production Unit - PFPU

Phase A System Study - Objective

To design a prototype of a modular food production unit for cultivation of potato plants in micro-gravity



Later in this Session!

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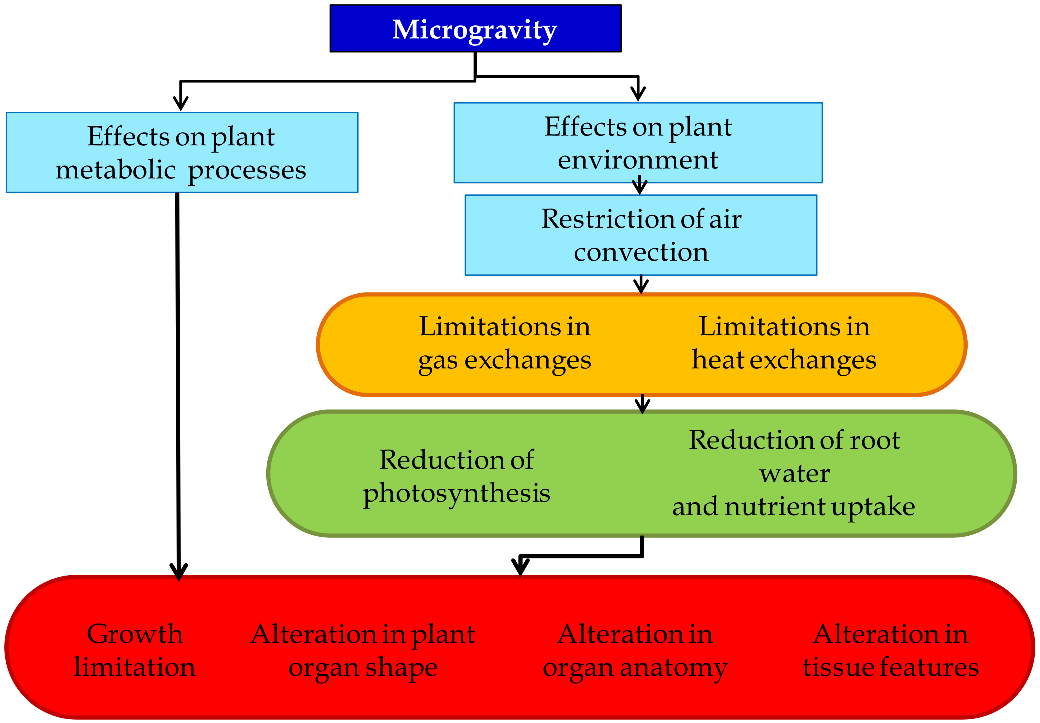
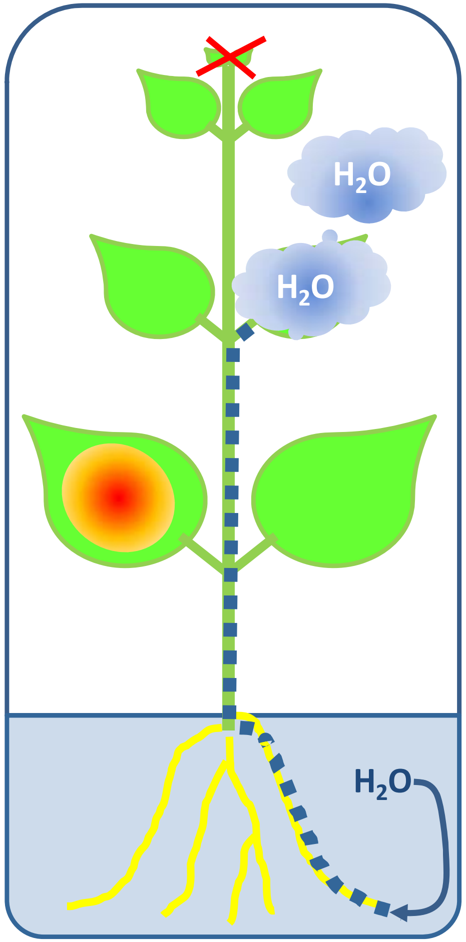
Telespazio
A Finmeccanica/Thales Company

PHASE 2
PFE

Flight experiment preparation:
Effects of microgravity
on plant morphological and functional traits

Water Across the Plant Systems (WAPS):
The decoupling of microgravity direct effects on plant growth from the indirect effects caused by restricted free air convection





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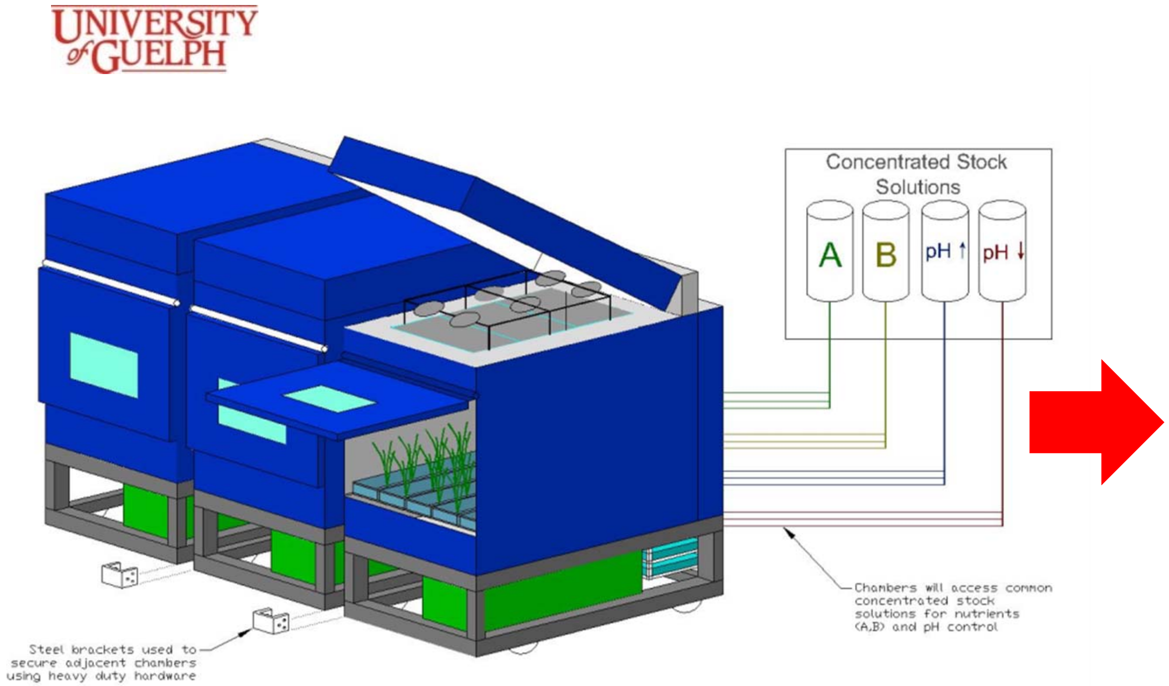
NTNU Norwegian University of Science and Technology
Université Blaise Pascal Clermont-Ferrand

Evolution of HPC technology and transfer to commercial applications

PHASE 4
TA



Phenotype testing chamber (Syngenta Company)

Human nutrition in Space

According to the mission food has to be:
- nutritionally balanced
- tasty
- appealing
- suitable to be consumed in weightlessness
- specially packed
- easy to store for a long time

In Space due to microgravity, radiation, environmental stress:
- modification of nutritional requirements
- changes of sensorial thresholds

High intakes of dietary antioxidants as countermeasure!

Plant bio-active molecules:
phenols, vitamins C and E, carotenoids, phytosterols

MELiSSA

PHASE 1
R&D

MELISSA food database
Menu definition

Indications from Long-term Bed-rest

Elaboration of menu

9 crops

(kale, lettuce, onion, potato, rice, soybean, spinach, tomato, wheat)

+

terrestrial ingredients

Elaboration of recipes

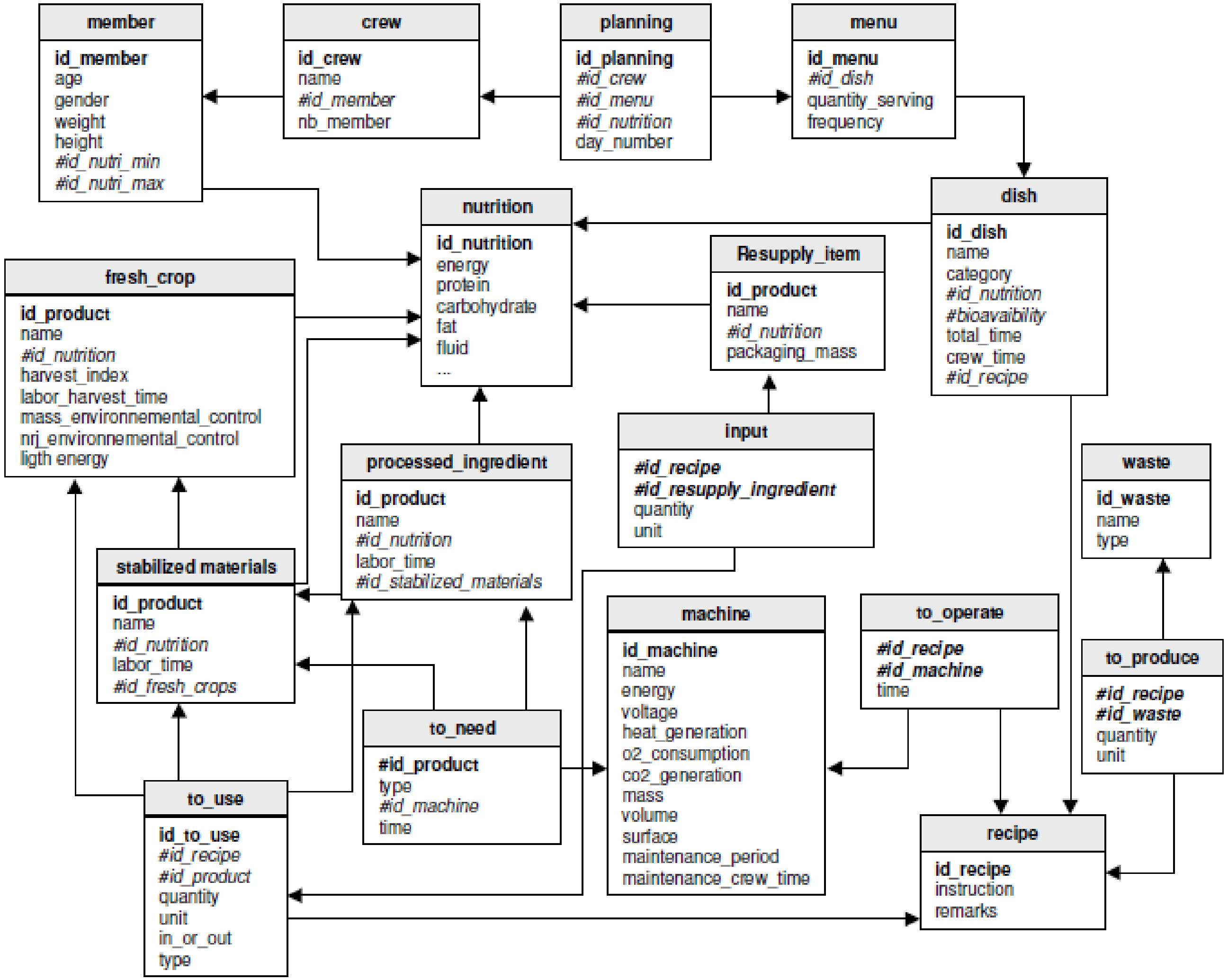
INGREDIENTS

- **Fresh plants:** plants directly usable as ingredient after the harvest, without preliminary transformations (e.g. tomato).
- **Stabilized ingredients:** obtained from fresh plants after a step of transformation (e.g. corn grains by threshing).
- **Produced ingredients:** obtained from stabilized ingredients (e.g. flour from grounding of corn grains).
- **Additional components:** ingredients not produced by MELiSSA loop but of terrestrial origin (e.g. chocolate).
- **Unused parts:** produced but not used in a recipe (e.g. the white part of the egg in a recipe needing the yellow part).

Bed-Rest Nutritional requirements
Water
Energy
Protein – Leucine
Na/K/Ca/P

PHASE 1
R&D

MELISSA food database Structure



Features considered:
- Harvest performance
- Nutritional interest
- Food process
- Culinary creativity
-

Food processing:
- energy
- mass
- volume
- crew time
- ...

MELISSA MENU

PHASE 1
R&D

Just a few recipes …

Gnocchis de pommes de terre
Tomates et oignons farcis
Nems de laitue
Soupe glacée à la tomate fraîche
Galettes de pommes de terre
Légumes en tempura
Pâtes aux algues et fondue de tomates
Risotto aux algues
Millefeuille de pommes de terre à la tomate
Riz au lait de soja
Salade « Melissa »
Tomates à la Provençale
Panacotta au lait de soja
Confiture de tomates vertes
Potage Parmentier
Barbajuans
Pain "Martien"

Astronaut's wishes of better food

- Cristoforetti (Italy, 2015-2016)

… of more than 300 !

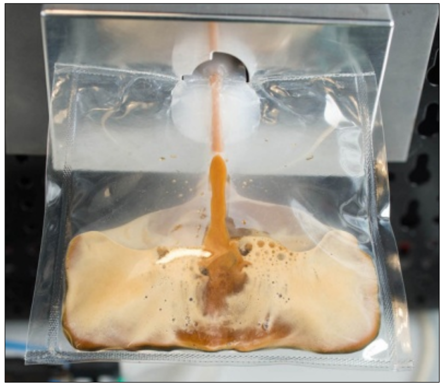
Space food

Apollo food (1968-1972)

Skylab food and tray (1973)

Shuttle food tray (1981-2011)

ISS (today)



After about 40 years (from the first Skylab Space Station), on August 10, 2015 **Astronauts snack on space-grown lettuce for first time (officially)**

Astronauts Scott Kelly and Kjell Lindgren (NASA) with Kimiya Yui (JAXA) snack on freshly harvested space-grown red romaine lettuce from Veggie experiment (NASA TV)

Conclusive remarks

Achievements

- Advancements in closed controlled environment technologies for higher plants
- Increase in knowledge on crops in hydroponics under controlled environment
- Knowledge in food characterization for life support

Addresses for future research:

- Cultivars/cultivation protocols for increasing harvest index
- Plant waste management and *in-situ* resources (re)-utilization
- Sensors for environmental conditions and plant health monitoring and control
- Plant/crop modelling
- Tools for microbial contamination detection and control
- Flight experiments to validate the scientific results and to test the sub-systems (biological and engineering)


THANK YOU
FOR YOUR
ATTENTION!
MELISSA